A More Comprehensive NDE: PCRT for Ceramic Components

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ABSTRACT. Process Compensated Resonant Testing (PCRT) has been demonstrated as an excellent alternative for ceramic parts, going beyond traditional resonance testing by applying pattern recognition algorithms and process control statistics to precise resonant data. PCRT is used for studying structural integrity and functional performance in a variety of ceramic parts. PCRT is a whole body inspection that detects internal defects such as cracks, voids, and inclusions. PCRT can also perform surface inspection of balls, using Surface Acoustical Waves. PCRT can be performed in real manufacturing time, and computer control eliminates operator error and subjectivity.

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INTRODUCTION

Ceramic material advancements have produced many new components to meet the needs of the growing engine technology requirements. Ceramic components, including seal elements and bearing components, provide higher stiffness, lower thermal expansion, lighter weight, increased corrosion resistance, and higher electrical resistance than comparable steel products. However, NDE techniques currently applied to these ceramics cannot keep pace with typical rates of manufacturing production. Traditional NDE methods (UT, ET, RT, and PT) often provide incomplete results when used to inspect ceramic components. This leads to a requirement for multiple costly and time-consuming inspections.

Process Compensated Resonant Testing (PCRT) has been demonstrated as an excellent alternative for inspecting ceramic parts that cannot be inspected with traditional NDE. PCRT goes beyond traditional resonance testing by applying pattern recognition algorithms and process control statistics to precise resonant data. PCRT is a trained method that learns which resonance variation is acceptable, and which is unacceptable, while also monitoring in-control processes.

Many ceramic materials, including Silicon Nitride and Zirconia, resonate extremely well, leading to very precise measurements and an exceptional ability to compare samples and populations of samples. In this study, PCRT is used for studying structural integrity and functional performance in a variety of ceramic parts used in aerospace, power generation and armor applications. The parts include ceramic balls with varying diameters, seal rings, and armor plates. PCRT is a whole body inspection and provides an assessment for structural integrity in terms of cracks, voids, inclusions, heat treatments, material properties, etc. as they relate to the ultimate performance of the parts. Cosmetic defects are not rejected. Parts with acceptable structural integrity and performance are separated from parts with manufacturing and structural and/or material deficiencies. PCRT can be performed in real manufacturing time, with inspection times measured in seconds, and is computer controlled for operator-independence. PCRT is limited in that it does not characterize the nature or location of the defect; it simply highlights the part as being statistically 'different' from the acceptable training population.

As an alternative to methods that can study only the surface of ceramic balls (hybrid bearing rolling elements), PCRT is used for studying both the internal structural integrity as well as the surface finish quality. Whole body inspection is performed using lower frequency modes sensitive to internal porosity or inclusions and to basic material properties. Surface Acoustical Waves are used to evaluate the outer surface for cracks and other stress-risers. The results from this study show that PCRT successfully sorts acceptable parts from unacceptable parts based on materials/structural integrity, functional performance and defects such as microstructure changes, c-cracks, density variation and inclusions. PCRT has been successfully implemented for inspecting production parts in many applications, and has reduced inspection costs tremendously while other uses have led to improvements in the manufacturing process. The pursuit of progressive improvements in the usage of PCRT, like any other NDE methods, is an on-going process.

PCRT should be used by ceramic part manufacturers to verify the quality of the manufacturing process, and to produce a supply stream of defect-free components. PCRT can also be utilized by assemblers and OEM's to verify the quality of the part stream, or to analyze components in a repair environment.

PROCESS COMPENSATED RESONANCE TESTING (PCRT)

Process Compensated Resonance Testing (PCRT) is a relatively young approach in NDE having its underlying technology developed in the late 1980's at Los Alamos National Laboratories. PCRT is based on the physics fundamental that any rigid component will resonate at specific frequencies that are a function of its mass, shape, and material properties. Material changes or flaws change the normal resonant pattern. While elementary resonance techniques may suffer from low-precision and a limited frequency range, PCRT utilizes high-precision resonance measurements across the range of 1 kHz to 15 MHz. Most resonance techniques do not have the ability to distinguish acceptable process variation from the effect of a small defect, as both cause changes in the resonance spectra. PCRT relies on proprietary software algorithms, developed to compensate for normal manufacturing variations, and novel algorithms for monitoring structural changes in a part over its life. These analytical tools combine to significantly reduce field failures of component, increase production yield, and optimize part life.

PCRT is a fundamental shift in NDE philosophy and applications. Current technologies strive to highlight indications that could represent structural deficiency in a component. PCRT accurately measures the structural similarity of a component to known good parts and is also able to measure the structural changes in a single part throughout its useful life. Proprietary pattern recognition software algorithms, called Sorting Modules, are developed to identify defects while compensating for normal manufacturing variations. The final product is a rapid, accurate, computer-controlled and operator-independent PCRT evaluation.

PCRT has been applied as a viable NDE technique on many different components and can be used on a wide range of materials including ceramics and most metals. Generally speaking, the size and geometry of components does not limit the application, with successful applications ranging from 3/8” diameter ceramic ball bearings up to 200 lb automobile engine blocks.

PCRT applies statistics, comparative analysis, and pattern recognition to precise resonance data. Measurements are taken using 3 contact PZT transducers – 1 used as a ‘drive’, and 2 used to receive. Swept sine waves are used to stimulate the part through a proprietary signal generator/processor. Resulting measurements have repeatability of .05% (standard deviation) or better. The PCRT system builds on its precision and statistics to create computer-based comparison algorithms that can sort parts into ‘good’ and ‘defective’ categories. The resulting inspection is objective, can be fully automated, requires no part preparation (other than drying), and generates no waste.

To deal with defects that have a significant effect on the bulk material properties, such as density variation or a crack in ceramic armor, the patented PCRT software utilizes a Mahalanobis-Taguchi System (MTS) statistical analysis to identify a multi-frequency central tendency or pattern that groups the good parts, and excludes many types of defects. Defects with a lesser effect on the resonant spectra are excluded with a secondary discriminator known as the Bias. This is all determined in ‘n-dimensional’ space; however, some simplified graphics are shown in Figure 1 (right hand graphic is actual PCRT software output).

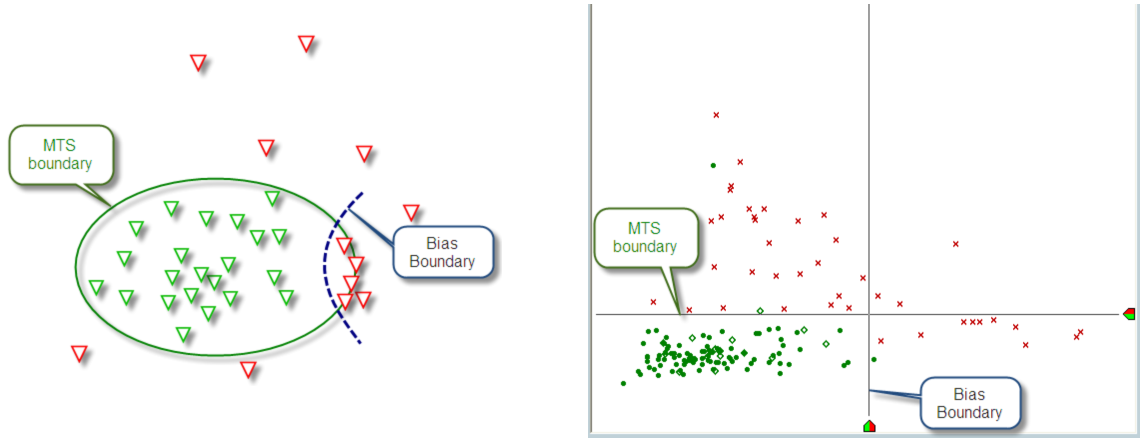

Figure 1. Graphic showing how MTS evaluates the ‘central tendency’ of a group, and Bias excludes parts that may also belong to the group, but show their own similarities(left). A PCRT software output (right), shows the sorting algorithm’s ‘passing’ region at the lower left, with the green dots indicating ‘good parts’. Red X’s represent ‘bad parts’ which fall outside both boundaries and will be rejected by the PCRT System.

Additionally, many ceramics end-users are concerned with much finer defects, such as surface cracking on ceramic balls or chipping of ceramic seals. These defects do not have a significant effect on the bulk material properties, but can dramatically affect the resonant frequency of degenerate modes, or modes where symmetrical resonances generally occur ‘on top’ of one another. When a surface crack or chip is present, modes that were previously identical are not any longer, and a ‘split’ is detected (see **Error! Reference source not found.**). The size of the resonance split is proportional to the size of the source of the asymmetry. By evaluating these splits statistically, a test can be developed to identify components with more asymmetry than is desired.

Both PCRT methods require a basic ‘training set’, or input model, to discover the range of ‘normal’ variation, and the source of differences, both acceptable and unacceptable. Sorting algorithms can use a ‘process control’ concept to reject samples outside of the range of ‘normal’ variation, or they can use a targeted ‘pattern recognition’ strategy to identify parts with the characteristics of specific defects.

APPLICATIONS OF PCRT

Hybrid Bearing Rolling Elements (Ceramic Balls)

New developments in gas turbine engines are driving the requirements of current bearing technology to its design limits in terms of material performance, capability, reliability and affordability. Hybrid ceramic rolling element/metal race bearing technology has proven itself to be a valid candidate to meet the needs of growing engine technology requirements. Compared to all-steel components, hybrid bearings offer increased load-carrying capability, decreased friction and heat generation, greater stiffness and corrosion resistance, lower coefficients of thermal expansion, and increased thermal stability.

Ceramic balls have proven to be robust in use provided that they are free of manufacturing defects. However, NDE techniques applied to ceramics for this class of bearing have proven to be ill-suited for quality-assurance inspections for typical rates of manufacturing production. The slow inspection rate and high inspection costs of current ceramic NDE methods may prevent hybrid bearings from being widely used in current or future fleets.

PCRT tests ceramic balls in a fixture similar to those shown in Figure 2. Inspection does not require any ball-rotation, and the balls can be loaded into the fixture by an automatic parts handling system. As the test does not require any human interpretation, the entire process can be automated. Testing times less than 2 minutes could be easily achieved with these methods.

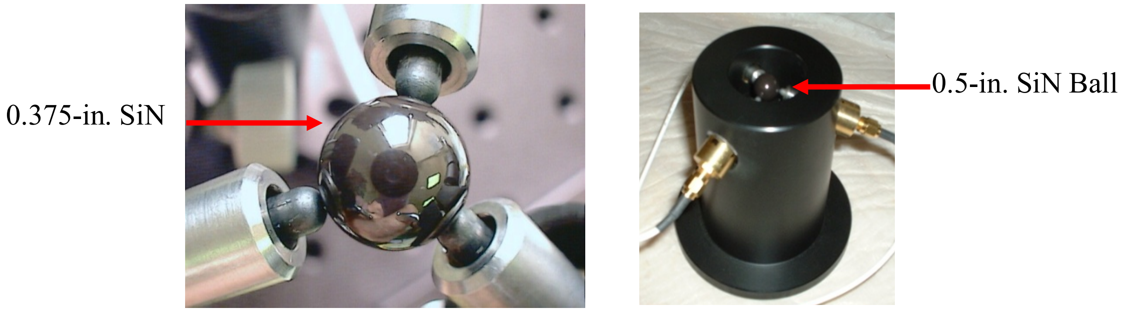

Figure 2. Typical Test Fixtures for Ceramic Balls

Lower-frequency resonances can be used to evaluate the spherical symmetry and identify bulk-body defects. Higher-frequency resonances, where surface or Rayleigh waves dominate, propagate without dispersion in an isotropic media and therefore, any distortion in the measured Rayleigh wave may be attributed to near surface flaws[1][2]. An example of this distortion is shown in Figure 3. The resonances exhibit peak splits and shifts in frequency and these are key characteristics that the PCRT System uses to classify a part as acceptable or unacceptable.

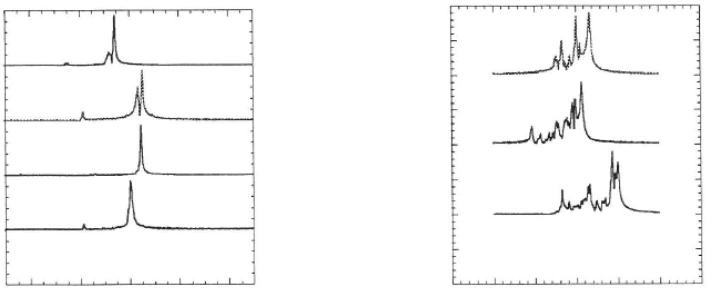

Figure 3. Resonances of Good Samples (left) and SAW-Like Modes Caused by Surface Defects (right).

Relatively low frequency resonances (first 10-15 modes) for the ceramic balls have proved capable of detecting a number of whole body and surface defects such as microstructure differences, surface chemistry / reaction layer defects, metallic inclusions, and density and raw material variation.

Smaller surface damage is detectable by higher order surface resonance. Figure 4 (left) shows peak splitting around 8.1 MHz due to a C-spall crack introduced into a 1.125-in. ball (via impact with a 0.375-in. ball). Figure 4 (right) shows peak splitting due to surface damage inflicted by a micro-hardness tester, resulting in chip and crack. These splitting characteristics are expected due to surface acoustic wave behavior, as described by Migliori [0], and were evident on many other resonances over the broadband range.

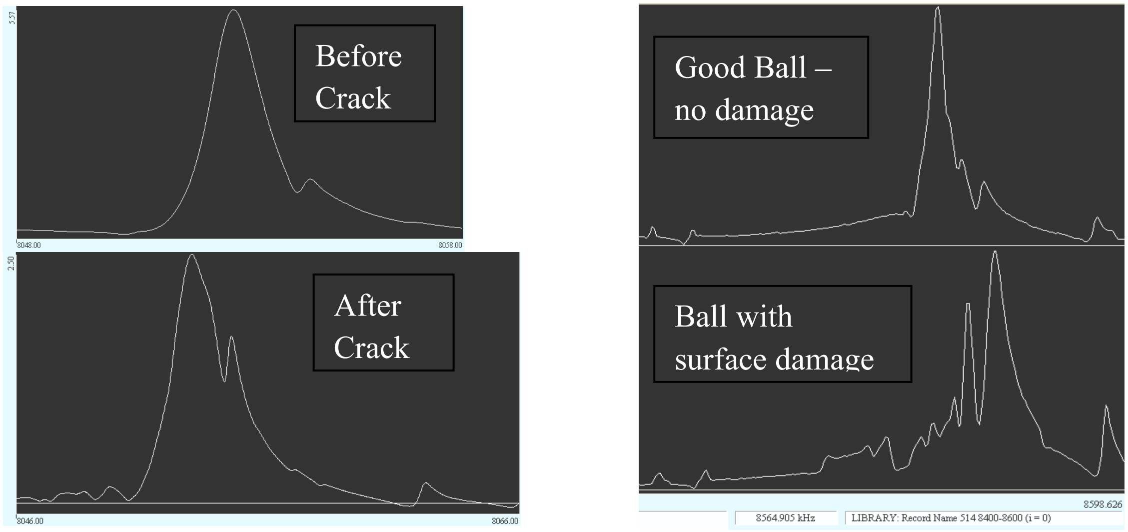

Figure 4. Resonance comparisons for balls with no surface damage, and balls with surface damage (c-cracks and/or surface chipping)

In a repeated study, a ball was impacted in a lesser manner to try to induce a 'smaller' c-crack. A ball free of surface defects was measured 15 times to provide a baseline. Although the ball had no defects, some resonance splitting was still observed, due to the difficulty in making a completely symmetrical specimen. Then the ball was impacted with another ceramic ball, with increasing force, to inflict surface damage. A crack was not detected with visual or dye-penetrant inspection until the 'cracked' stage, shown in Figure 5, but perhaps the effect of the initial 'impacts' (which did not produce a visible crack) are detected. Five resonances between 6 and 9 MHZ were studied in this experiment, with all showing similar results for the 'cracked stage'. Only the highest frequency peak studied (shown above) shows a difference in the 'impacted' stage. These studies continue.

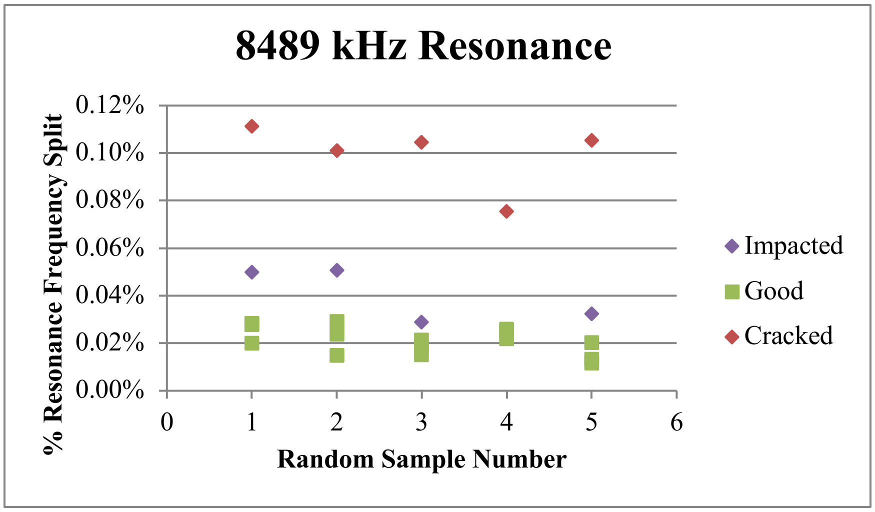

Figure 5. 8.5 MHz response showing change in 'split size' for a ball with induced c-crack.

Resonant Frequency data can also be used for process control, receiving inspection, and supplier comparison. **Error! Reference source not found.** shows results for a separate set of balls. This type of variation, seen in low frequency 'bulk resonant modes' is indicative of variation in either the dimension, or base material properties of the balls. As the dimensions are very tightly controlled, it is assumed the variation is due to material property difference. Resonant Ultrasound Spectroscopy (RUSpec) measurements of the Young's Modulus varied noticeably, from a statistical distribution standpoint, but only about 1.5% between the batches.

Evaluation of other sample sets shows similar results. Variation can be seen between batches from the same supplier, and more obviously between balls from different suppliers. Some batches show relatively consistent variation (similar to Batches 2 and 3 in **Error! Reference source not found.**), and others show dramatically different results (Batches 1 and 2 in **Error! Reference source not found.**). PCRT can be a valuable part of a supplier evaluation program, or in-house process control, identifying trends and changes in the product that can be traced back to process changes and manufacturing conditions.

Ceramic Seals

Vibrant has completed some initial feasibility studies of the use of PCRT for ceramic seal NDE. The seals were evaluated for process control opportunity (batch comparison), chips and cracks.

PCRT data showed a clear difference between the good parts and the cracked part provided. The crack showed both as a frequency 'shift', due to bulk property changes, and a 'split', due to the break in the ring's symmetry. Nearly every resonant peak was affected, and the defective part was easily identified. Standard PCRT testing does not specify the 'type' or 'location' of defects detected, but with further PCRT study, and/or application of more traditional NDE methods, a comprehensive study of the cause and effect of the defect can be completed.

The chipped parts show only the 'splitting' characteristic in the resonance spectra, because the chip does not have as significant an effect on the overall strength of the part. Vibrant validated these findings by inflicting a chip similar to a production sample, in an otherwise 'good' part, and noting the spectra 'before' and 'after' (Figure 6). Split size has been shown in many applications to correlate well to the size of the defect present. Splits will also identify internal sources of asymmetry, such as porosity, inclusion, and chemistry anomaly. The chip sizes evaluated to date are readily detectable by a PCRT system.

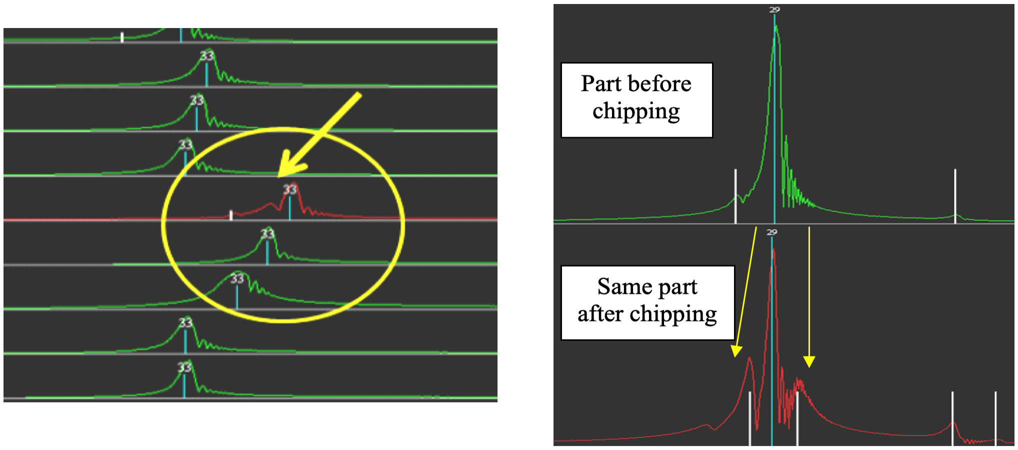

Figure 6. Stack of Resonance spectra showing 'split' evident in chipped part (left) and high resolution spectra of part before and after chipping (right). Peak splitting increased significantly due to chip.

Ceramic Armor

PCRT can also be used to examine ceramic armor plates for production conditions and defects. The Army Research Laboratory has recently commissioned a system to test armor plates for density variation and cracks following a feasibility study that included a successful 'blind' test. The system will be used by BAE for the inspection of multiple part numbers. Density changes produce a proportional shift in resonant frequency, and variation outside of the 'normal' controlled process is easily identified. Cracking leads to significant changes in the resonant spectra, such that the 'normal' resonant frequency patterns are not evident.

PCRT data has also been used by other organizations to compare armor plate suppliers, with notable differences in the stability of production processes. Resonance data for the armor plates is high quality, allowing very precise, repeatable non-destructive evaluation in a matter of seconds. Figure 7 shows a snapshot of such data for a group of good CMC coupons with varying levels of porosity.

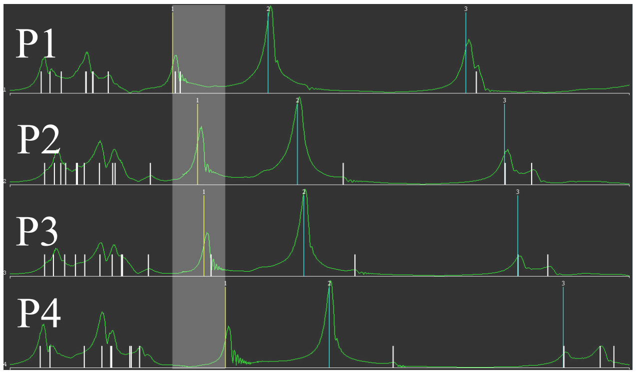

Figure 7. CMC Coupon spectra showing shift in resonance due to varying porosity.

The resonant spectra indicate that PCRT is sensitive to variations in porosity for a given CMC part geometry. The resonant spectra show a clear trend in resonant frequencies vs. porosity. As porosity decreases from "High" to "Low" from P1 to P4, the resonant peaks shift to the right (increasing frequency), generally indicating increased part stiffness.

As demonstrated by the CMC coupons, some armor sets evaluated display significant process variation in the 'good' parts. Detecting defective conditions in the presence of this variation will require PCRT's patented pattern recognition techniques. Figure 8 shows the output of the VIPR (Vibrational Pattern Recognition) software that identifies the MTS and Bias discriminators for a larger data set of ceramic armor plate.

Conclusions

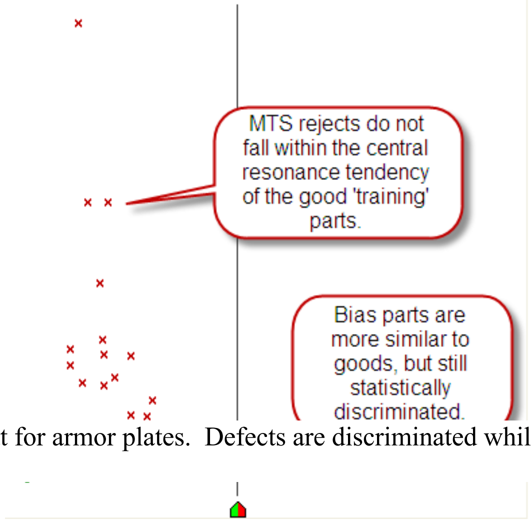

Figure 8. PCRT's VIPR output for armor plates. Defects are discriminated while process variation is accommodated.

Process Compensated Resonant Testing (PCRT) has been demonstrated as an excellent alternative to traditional NDE for inspecting both whole body and surface defects in a wide variety of ceramic parts. PCRT goes beyond traditional resonance testing by applying pattern recognition algorithms and process control statistics to precise resonant data, allowing the system to learn which resonance variation is acceptable, and which is unacceptable, while also monitoring in-control processes. PCRT is a fundamental shift in NDE philosophy and applications, working to meet the present and future NDE needs of aviation technology.

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